

Charmonium suppression in pA collisions

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The new high precision data on charmonium production in proton-nucleus collisions by the E866/NuSea collaboration at Fermilab allow — together with older data at lower energies — to fix a unique set of parameters for the standard production and absorption scenario of charmonium in a proton-nucleus reaction. In this scenario the $c\bar{c}$ pair is formed in an octet state, emits a gluon and continues its radial expansion in a singlet state until it has reached the charmonium radius. In all three phases it can interact with the nuclear environment. We find that the lifetime of the octet state is much shorter than acceptable on physical grounds. This challenges the physical reality of the first phase in the standard scenario.

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I. INTRODUCTION

Since the suppression of J/ψ 's has been proposed by Matsui and Satz as a signal for a quark-gluon plasma formation more than a decade ago [1] a lot of experimental efforts have been devoted to use them for the quest of the formation of a quark gluon plasma created in ultra-relativistic heavy ion collisions. For small systems, where the creation of a plasma is not expected, the measured absorption can be well explained without invoking a plasma. At Quark Matter 1996, the first results on the heavy system Pb-Pb have been reported [2] by the NA50 collaboration and it has been argued that they show an abnormal suppression (as compared to the extrapolation from small systems) which may be interpreted as a hint for the formation of a quark gluon plasma. This triggered a lively and still ongoing debate about the conclusions of this observation.

Before one tries to understand the J/ψ suppression seen in heavy ion collisions it is necessary to understand that obtained in pA collisions where the reaction is much more under control. There one expects that the shape and the density of the nucleus does not change during the reaction. Recently new data have been advanced by the Fermilab group E866/NuSea [3], where for the first time differences between the absorption of J/ψ 's and ψ 's have been observed. This fact as well as the high precision of these data allow to fix the parameters of the standard scenario [4,5].

Here, we present a model for the charmonium absorption in proton-nucleus collisions which is based on the standard scenario described in Section II. We have limited the ingredients to the minimum that allows the

description of the Fermilab data in the whole x range. Several initial state effects such as gluon shadowing [6], energy loss [7,8], or quantum coherence [9] could affect somehow charmonia production at Fermilab energies. However, since Drell-Yan production does not show a significant nuclear dependence, we have assumed that those effects are relatively less important and their consideration would imply an unnecessary complication. We have checked that inclusion of gluon shadowing does not alter the conclusions one can draw from our study, but changes somewhat the present set of effective parameters. Taking the recent results of the E866/NuSea collaboration at Fermilab [3], we determine a set of parameters for the standard scenario. The same set of parameters allows the description of almost all other available data on charmonium suppression in pA collisions, including the majority of NA3 data points [10], those of NA38 [11] and those of E772 [12]. We show that the functional form of the model allows to describe the whole body of data and that its parameters are rather precisely fixed by them. We show as well that the x_2 scaling predicted by the model is compatible with high-energy data. We do not claim that our result excludes other reaction mechanisms (as we will see there is good evidence for that on physical grounds) but stress that on the basis of the presently available data one cannot distinguish experimentally between them.

II. MODEL FOR CHARMONIUM ABSORPTION IN PROTON-NUCLEUS REACTIONS

In pA collisions the production of $c\bar{c}$ states is supposed to be proportional to the atomic mass A of the target, as

it is the case for the Drell-Yan process. Thus, the charmonium states are produced anywhere in the nucleus with a probability directly proportional to the local nucleon density. We consider here J/ψ 's, ψ' 's and χ 's. Feeding is important: only 50% of the observed J/ψ 's are primarily J/ψ 's, the other 50% come from radiative decays of χ 's (43%) and ψ' 's (7%) [9]. The spin of the χ state may play a role in the χN cross section [13], but we neglect this effect here.

The $c\bar{c}$ pair is not created in a fully formed state, with its final radius. We assume that the transverse distance between the quarks increases linearly with time. In the $c\bar{c}$ rest frame we write

$$r_{c\bar{c}}(\tau) = \begin{cases} r_0 + v_{c\bar{c}} \tau & \text{if } r_{c\bar{c}}(\tau) \leq r_i, \\ r_i & \text{otherwise,} \end{cases} \quad (1)$$

where i stands for J/ψ , ψ' and χ . The final radii r_i of the different states are determined by microscopic calculations. The limits chosen are 0.43 fm for J/ψ , 0.87 fm for ψ' and 0.67 fm for χ [14]. $v_{c\bar{c}}$ is the sum of the c and \bar{c} velocities i.e. $v_{c\bar{c}} = 2v_c$. $v_{c\bar{c}}$ and the initial radius r_0 are taken as free parameters. An alternative possibility for the $c\bar{c}$ expansion, $r \propto \sqrt{\tau}$, has been proposed in [15]. We have checked that no definite conclusion may be drawn about which one is actually at work. The main point is that the expansion is important in the kinematical region where one can distinguish J/ψ from ψ' .

The $c\bar{c}$ pair is formed by two-gluon fusion in an octet state $(c\bar{c})_8$ which later on emits a gluon and neutralizes its color. We assume that the emission occurs after a color neutralization time $\tau_{8 \rightarrow 1}$ in the rest frame of the $c\bar{c}$ pair, independently of its velocity. $\tau_{8 \rightarrow 1}$ is the third parameter of the model. In the nucleus rest frame, the lifetime of the octet state increases with x_F , due to Lorentz dilatation. We will see that this fact is responsible for the increase of absorption with x_F , as seen in data. This would not be the case if the octet-singlet transition occurred after a constant time in the nucleus rest frame (a natural hypothesis if neutralization was caused by interactions with the surrounding nucleons). According to [9,16] the octet lifetime should be of the order of 0.3 fm. We will see that the new data allow for a precise determination of the color neutralization time $\tau_{8 \rightarrow 1}$.

Some authors have argued that the production can partly proceed via a direct color singlet state [17]. Although a priori distinct from color evaporation they have shown that it is not presently possible to clearly disentangle those two possibilities. Since on the one hand the x_F dependence of the color singlet production fraction is unclear and on the other hand the fit does not improve if one incorporates this effect we assume that $c\bar{c}$ pairs are always created in a color octet state.

The singlet-nucleon absorption cross section $\sigma_{(c\bar{c})_1 N}$ depends on both the transverse radius $r_{c\bar{c}}$ of the $c\bar{c}$ pair and its energy. In QCD the total cross section for a compact singlet state should be proportional to the square of its radius [18] and we write $\sigma_{(c\bar{c})_1 N} = \sigma_{\psi N}(s) \cdot (r_{c\bar{c}}/r_\psi)^2$.

Next, we need the energy dependence of the ψN cross section in the kinematical region corresponding to available data, that is in the region around 10 GeV and above. In this range it may be related to that for J/ψ photo-production and to the small x gluon distribution [19] leading to $\sigma_{\psi N}(s) = \sigma_1 \cdot (\sqrt{s}/10 \text{ GeV})^{0.4}$ where \sqrt{s} is the center of mass energy of the $c\bar{c}N$ system. Thus, the time dependent cross sections for singlet states is given by

$$\sigma_{(c\bar{c})_1 N}(\tau) = \sigma_1 \cdot \left(\frac{\sqrt{s}}{10 \text{ GeV}} \right)^{0.4} \left(\frac{r_{c\bar{c}}(\tau)}{r_\psi} \right)^2, \quad (2)$$

where the radius $r_{c\bar{c}}$ is given by (1) and σ_1 is the cross section for a fully formed J/ψ with incident energy $\sqrt{s} = 10 \text{ GeV}$. σ_1 is the fourth parameter of our model and should be of the order of a few mb [19].

The present model gives a unified treatment for J/ψ , ψ' and χ since the only difference in the cross sections comes from the final radii r_i . Consequently, one expects for small x_F where the J/ψ is formed before leaving the nucleus a difference in the absorption between J/ψ , ψ' and χ , as the ψ' and the χ radii are bigger than that of the J/ψ . Indeed the E866/NuSea group found a different absorption for $x_F \leq 0.2$ (cf. Figs. 1 and 2). At high x_F , the different states will behave similarly because the $c\bar{c}$ leaves the nucleus before it has reached the J/ψ final size, due to Lorentz dilatation. Strictly speaking this is true if one neglects the mass difference between charmonia. For given beam energy and charmonium velocity x_F is proportional to the charmonium mass implying, e.g., a systematic 20% shift of ψ' with respect to J/ψ . This is somewhat reduced by the fact that J/ψ comes partly from radiative decay of χ and ψ' and further by the fact that what one needs in order to compute the $c\bar{c}$ velocity at a given x_F is the intermediate $c\bar{c}$ mass. In lack of a good description of this mass effect and noticing that present ψ' data are not precise enough to be analyzed at this level of accuracy, we assumed that the intermediate $c\bar{c}$ and all charmonia have the same mass $m_{c\bar{c}} = (m_\psi + m_{\psi'})/2 = 3.4 \text{ GeV}$.

The interaction between the octet state and nucleons is mainly responsible for the increase of absorption with increasing x_F observed at Fermilab. The large x_F region is dominated by $c\bar{c}$ pairs which have left the nucleus in the octet state. The absorption cross section between octet states and nucleons $\sigma_{(c\bar{c})_8 N}$ may be of the order of 20 mb [9], that is much larger than the singlet cross section. The usually quoted value of 6 mb in hadroproduction would be interpreted in the present scenario as an average between singlet and octet cross sections. Since the energy dependence is related to gluon dynamics, we assume that it is the same for $\sigma_{(c\bar{c})_8 N}$ and $\sigma_{(c\bar{c})_1 N}$. The octet cross section is taken to be independent of the radius of the pair $(c\bar{c})_8$:

$$\sigma_{(c\bar{c})_8 N} = \sigma_8 \cdot \left(\frac{\sqrt{s}}{10 \text{ GeV}} \right)^{0.4}. \quad (3)$$

σ_8 is the fifth and last parameter of the model.

If one assumes singlet states only, the A to p production ratio approaches 1 at $x_F = 1$ because the large gamma factor between the $c\bar{c}$ pair and the laboratory frame does not allow an expansion of the $c\bar{c}$ system while traveling through the nucleus. Thus the cross section (2) is small and so is the absorption.

III. RESULTS

Quantitative results were obtained with a Monte-Carlo simulation. The computation is done by first generating $3A$ random numbers, the first $3(A - 1)$ describing the positions of $A - 1$ static nucleons inside the nucleus and the 3 last localizing the creation point of the charmonium inside the nucleus. From this creation at the proper time $\tau = 0$, we follow the charmonium on its way through the nucleus in the z direction, $z(\tau) = z_0 + \beta\gamma\tau$. The charmonium velocity β in the nucleus rest frame is determined by x_F (see Section IV). The charmonium neutralizes its color at time $\tau_{8 \rightarrow 1}$ and expands as expressed by (1). If the transverse distance between the charmonium and a nucleon becomes smaller than $\sqrt{\sigma(\tau)/\pi}$ we assume that the charmonium is absorbed.

We made a fit to the J/ψ suppression in tungsten normalized to beryllium, measured by the E866/NuSea collaboration [3], with the five parameters described in the previous section. We obtain the following parameters: $r_0 = 0.15$ fm, $v_{c\bar{c}} = 1.85$, $\sigma_1 = 2.1$ mb, $\tau_{8 \rightarrow 1} = 0.02$ fm and $\sigma_8 = 22.3$ mb. This set of parameters is used to calculate the results for all other energies and targets. The influence of a change of these parameters on the results is discussed in Section VI.

In Fig. 1 we compare our calculation with the recent E866/NuSea results of proton-nucleus reactions at 800 GeV. In this experiment the absorption ratio

$$R(A/\text{Be}) = \frac{9\sigma(A)}{A\sigma(\text{Be})}, \quad (4)$$

for W and Fe has been measured. First of all we see that below $x_F = 0.2$ the absorption of J/ψ and ψ' is different. It is this fact which allows to determine the parameters of our model precisely. We see as well that the absorption has a minimum around $x_F = 0.1$. As we will discuss later in detail the increase at large x_F is caused by octet state-nucleon collisions whereas that at negative x_F comes from collisions of the fully formed charmonium states with nucleons, thus explaining the difference between J/ψ and ψ' absorption. The above parameter set describes data quite well in the whole measured x_F range and for the two different ratios (notice that the fit was performed with the W to Be production ratio only).

In Fig. 2 we show the same result in the alternative representation

$$\alpha = 1 + \frac{\ln R(W/\text{Be})}{\ln 184/9}. \quad (5)$$

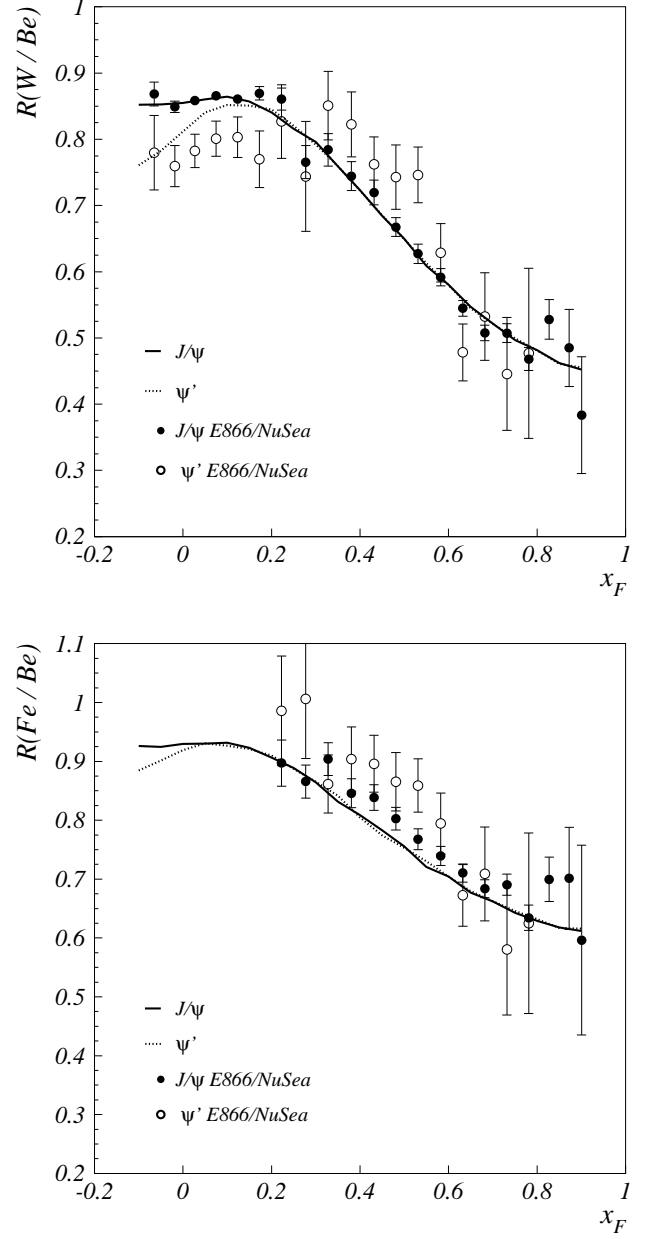


FIG. 1. Ratio $R(A/\text{Be}) = (9/A) \cdot \sigma(A)/\sigma(\text{Be})$ versus x_F of produced J/ψ 's (black circles) and ψ' 's (white circles) for W (top) and Fe (bottom). The lines are the results of our model.

A thorough study of this quantity [20] has shown that E866/NuSea results are compatible with earlier less precise results at 800 GeV and for various nuclei [12]. We present them here for completeness though in contradistinction to the E866/NuSea data they are not corrected for p_T acceptance [20].

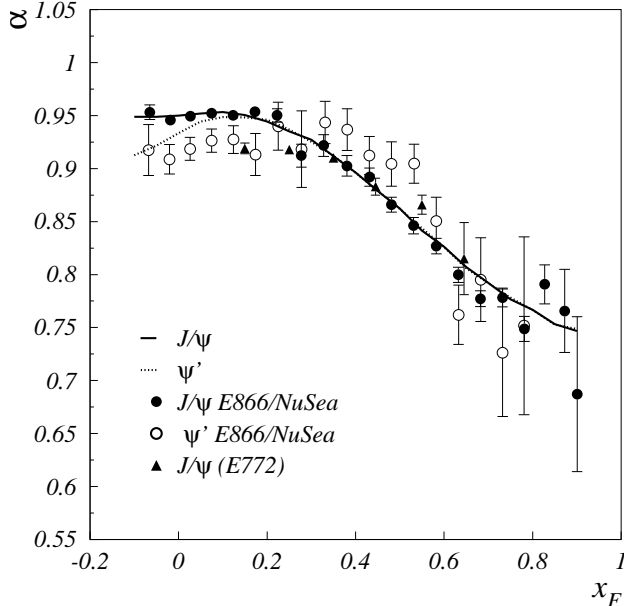


FIG. 2. $\alpha = 1 + \ln(R(W/\text{Be}))/\ln(184/9)$ versus x_F from E866/NuSea for 800 GeV/c protons as compared to the results of the calculation. E772 data are also shown for comparison.

The NA38 collaboration measured the J/ψ production for several targets (C, Al, Cu and W) at a beam energy $E_p = 450$ GeV [11]. The center of mass rapidity range is $[-0.4, 0.6]$ corresponding to $-0.1 \leq x_F \leq 0.15$. The comparison with our model is displayed in Fig. 3, with x_F taken as 0.05.

Finally, we compare our model with NA3 data [10]. Measurements were done with proton as well as pion beams on a proton and on a platinum target, at 200 GeV. Here, one can compare data with the model for $0 \leq x_F \leq 0.6$. One observes in Fig. 4 a fair agreement except for the two largest x_F values.

For the largest x_F value the deviation is large and the trend shown by large x_F NA3 data points cannot be described in our model. This may be the signal that some energy loss of the incoming gluon manifests itself since a loss as given in Ref. [7] would indeed have more influence at smaller energies and larger x_F . We found that the suppression seen for the large x_F NA3 data points may be explained with an energy-independent 1 GeV/fm energy loss of the incoming gluons in addition to the nuclear suppression considered so far. We have checked that such a rate gives a negligible effect at 800 GeV and that the corresponding rate for quarks is compatible with Drell-Yan measurements at 280 GeV [21] and 800 GeV [22].

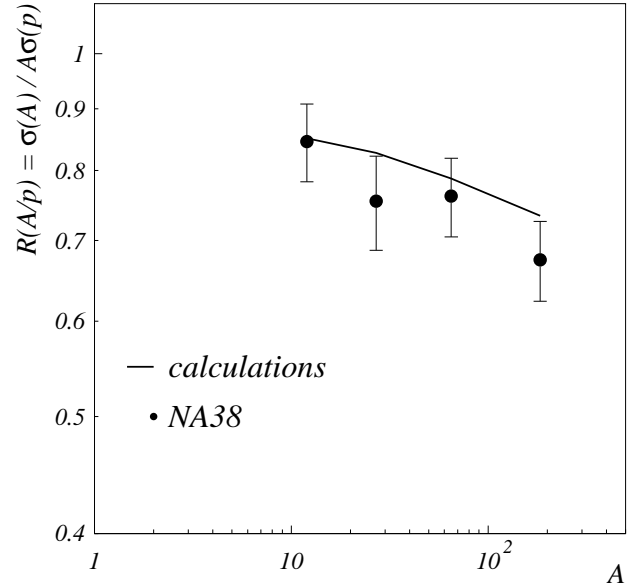


FIG. 3. J/ψ absorption for various nuclei in $p(450 \text{ GeV})+A$ reactions from NA38 as compared to the calculation.

There are nevertheless some weak points in this explanation:

- the energy dependence of energy loss is not clear [7,8];
- the energy loss also affects the ratio at low x_F for 200 GeV which becomes more suppressed than seen in the data;
- the pion beam NA3 data do not show a strong suppression of J/ψ 's at large x_F ;

which all together prevent us from drawing a firm conclusion on the relevance of energy loss.

Is there Scaling? Once a good reproduction of the raw data has been achieved, it is natural to ask whether a more unified picture is possible, exploiting scaling effects. In the present scenario, the absorption of charmonium states is entirely determined by the γ factor of the $c\bar{c}$ pair in the nucleus frame. Therefore, the model implicitly contains a γ scaling.

The value of γ is directly related to the momentum fraction x_2 in the target nucleon of the gluon which produces the $c\bar{c}$ pair. From $\gamma = E_{c\bar{c}}/m_{c\bar{c}}$, $E_{c\bar{c}} = x_1 E_p$ and $m_{c\bar{c}}^2 = 2x_1 x_2 m_p E_p$ we find

$$\gamma = \frac{m_{c\bar{c}}}{2x_2 m_p}. \quad (6)$$

With $m_{c\bar{c}}$ fixed as explained in Section II, the scaling with γ thus yields a scaling with x_2 .

A comparison of the E772 (which are in agreement with the more precise E866/NuSea data) with the NA3 data led to various conclusions in the literature. In [23] a

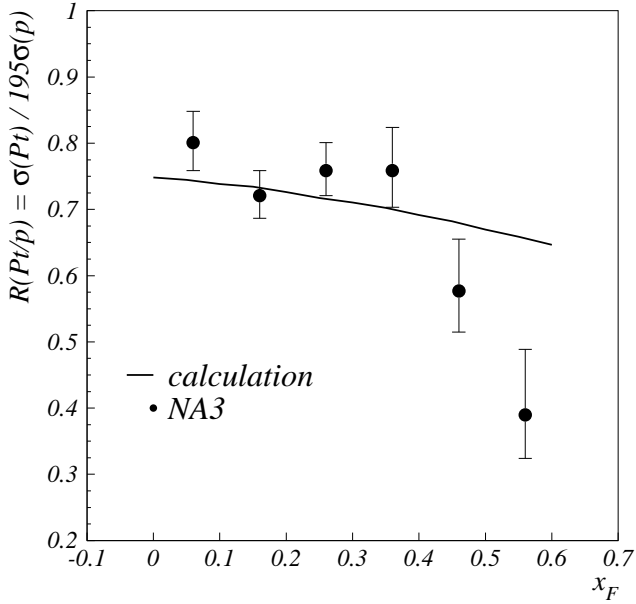


FIG. 4. Ratio of J/ψ 's produced in $p(200 \text{ GeV})+\text{Pt}$ and $p(200 \text{ GeV})+p$ versus x_F from NA3 as compared to the calculation.

good evidence was found for x_2 scaling using pion beam data, whereas in [12] scaling was found in x_F and not in x_2 . Since NA3 and E866/NuSea suppression ratios are consistent for $x_2 \geq 0.06$, all conclusions depend on the small x_2 , i.e. large x_F , NA3 pA data.

IV. THE SIGNIFICANCE OF THE DIFFERENT KINEMATICAL REGIONS

We now discuss in more detail which of the above-mentioned processes affect the suppression at a given x_F value.

Since $\tau_{8 \rightarrow 1}$ is smaller than the formation time, one can distinguish three $c\bar{c}$ states: (a) a $c\bar{c}$ still in a color octet state, (b) a $c\bar{c}$ already in the singlet state but still expanding and finally (c) a fully formed charmonium state. Fig. 5 shows in which state the surviving $c\bar{c}$ pairs leave the nucleus as a function of x_F in the reaction $p(800 \text{ GeV})+W$. We see that at large x_F the octet fraction is large whereas at negative x_F values almost all $c\bar{c}$ pairs have lost their color at this stage.

A complementary information is provided in Fig. 6. Here we display in which state the non surviving $c\bar{c}$ pairs are absorbed, again as a function of x_F . This figure shows which kinematical region is sensitive to the different cross sections and formation times. At large x_F values the absorption rate is sensitive to σ_8 only. At intermediate x_F ($x_F \in [0, 0.2]$), one encounters not fully formed singlet $c\bar{c}$ states. The corresponding singlet cross section is weak, so is the associated suppression. Therefore the absorption has a minimum in this region. For $x_F < 0$, the absorp-

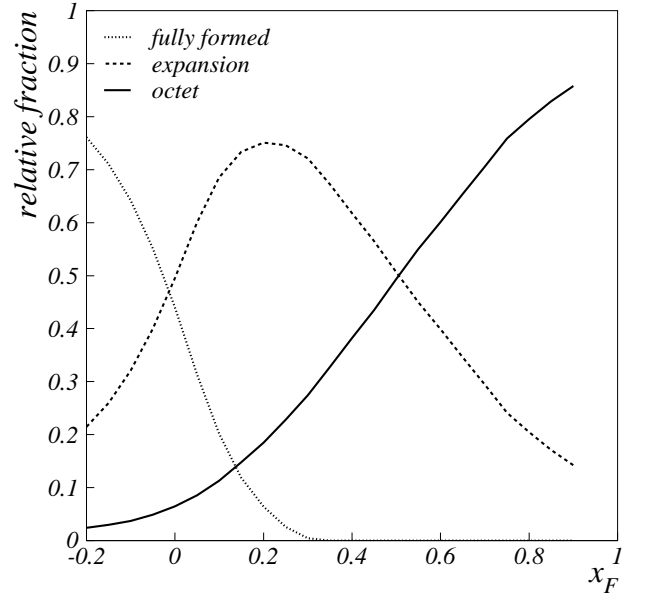


FIG. 5. Relative fraction of the different states, (a), (b) or (c), of the $c\bar{c}$ pairs when leaving the nucleus in $p(800 \text{ GeV})+W$.

tion is mainly governed by states in expansion and fully formed states. Almost 50% of J/ψ 's are absorbed in a fully formed state at $x_F \approx -0.1$. Therefore, differences between the charmonium states can be observed in this kinematical region.

V. SENSITIVITY TO THE FIT PARAMETERS

Our fit yielded a minimum at $\tau_{8 \rightarrow 1} = 0.02 \text{ fm}$. In order to quantify this observation we performed several fits in which $\tau_{8 \rightarrow 1}$ was fixed and the other parameters were allowed to vary freely. In Fig. 7 the χ^2/ndf for different values of $\tau_{8 \rightarrow 1}$ are presented. We see a rather sharp minimum around $\tau_{8 \rightarrow 1} = 0.02 \text{ fm}$. Thus we can conclude that the data determine the octet lifetime precisely.

We show in Fig. 8 and 9 how precisely data determine the other parameters for $\tau_{8 \rightarrow 1} = 0.02 \text{ fm}$. As discussed in the former section we can almost separate two regions: $x_F > 0.4$ where the physics is determined by the properties of the octet state and $x_F < 0$ where the singlet state dominates. Fig. 8 shows the dependence of our results on σ_8 . If σ_8 decreases the absorption becomes weaker. This is a dramatic effect for large x_F , which in consequence determines this cross section quite precisely.

The variation of our results for J/ψ and ψ' production as a function of the three parameters which describe the interaction of the singlet state is shown in Fig. 9. Here x_F is fixed to -0.1 . We see that all these parameters are not very precisely determined. A change of the parameters by 50% changes the results by about 5%. Data at lower x_F - for both ratios $R(W/Be)$ and $R(Fe/Be)$ - would therefore

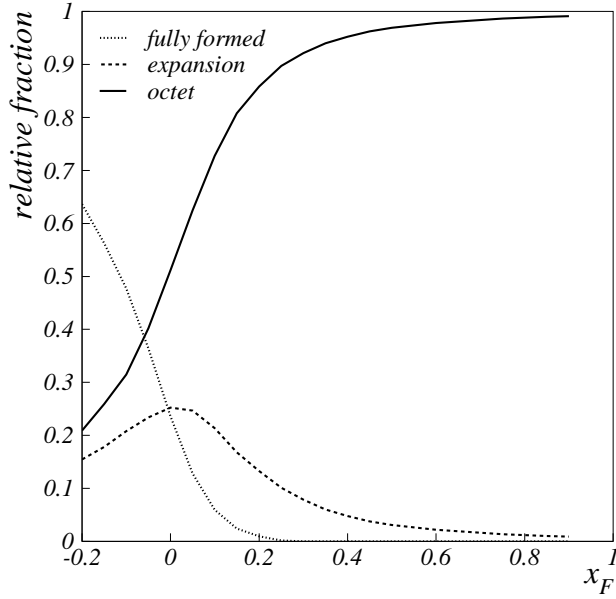


FIG. 6. Relative fraction of the different states of the $c\bar{c}$ pairs at the time of absorption by a nucleon in $p(800 \text{ GeV})+W$.

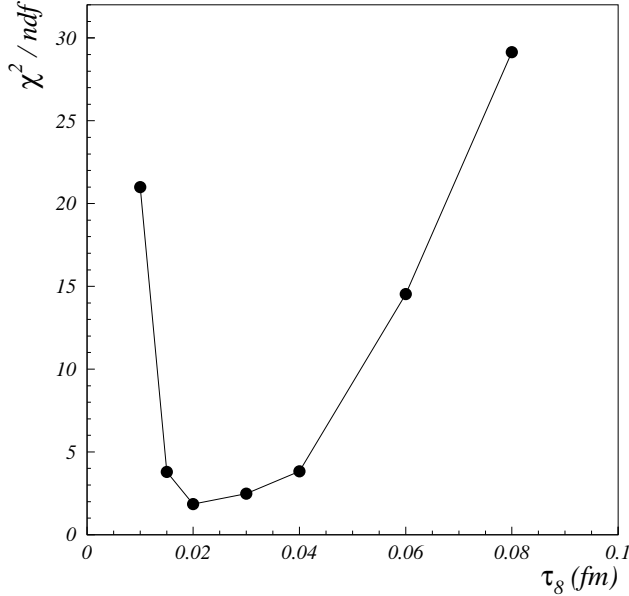


FIG. 7. χ^2/ndf for different $\tau_{8 \rightarrow 1}$. The number of degrees of freedom is 35.

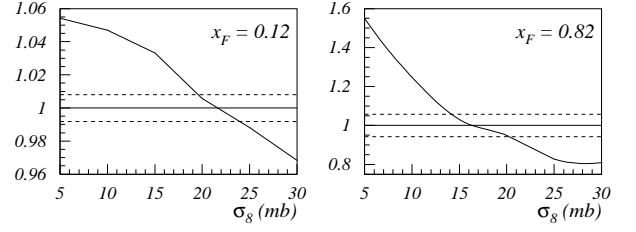


FIG. 8. Influence of σ_8 on charmonium absorption in W and Be. The ratio of the calculation and the E866/NuSea data is shown for J/ψ at $x_F = 0.12$ (left) and $x_F = 0.82$ (right).

be very helpful to fix them more precisely.

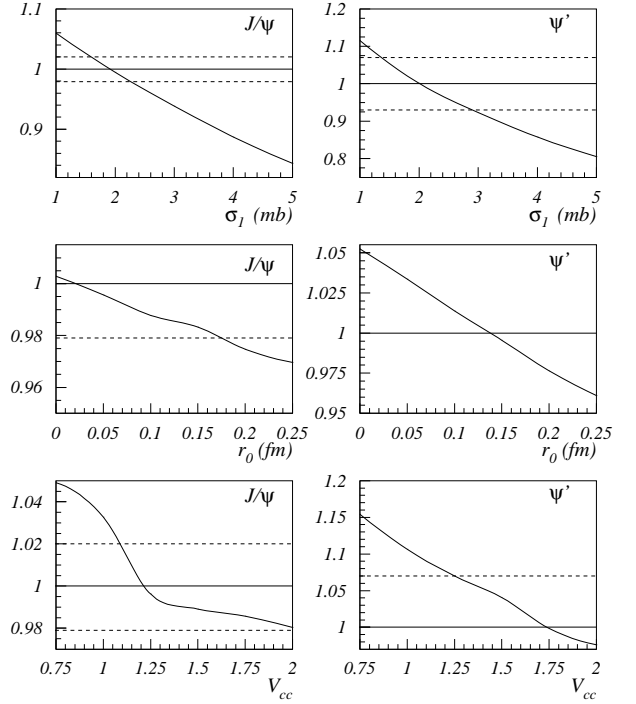


FIG. 9. Influence of σ_1 , r_0 and $v_{c\bar{c}}$ on charmonium absorption in W and Be. The ratio of the calculation and the E866/NuSea data is shown for J/ψ (left) and ψ' (right) at $x_F = -0.065$.

The initial radius r_0 and the quark-antiquark relative velocity $v_{c\bar{c}}$ were given by the fit as $r_0 = 0.15 \text{ fm}$ and $v_{c\bar{c}} = 1.85$. Accordingly, the time needed to form a J/ψ is

$$\tau_f = \frac{r_\psi - r_0}{v_{c\bar{c}}} \approx 0.15 \text{ fm}. \quad (7)$$

For a longer formation time the ψ' 's would behave as the J/ψ 's even at negative x_F values, in contradiction to the experimental results. A shorter formation time fails to explain the rise of α between $-0.1 \leq x_F \leq 0.1$. Calculations based on realistic potentials for quark-antiquark

bound states give a somewhat higher value (0.3 fm) for the time of formation [24].

VI. COLOR OCTET LIFETIME

The fitted value $\tau_{8 \rightarrow 1}$ is very small. In order to understand the origin of such a short time in the present approach we concentrate on the large x_F Fermilab data. Here the suppression is important and absorption in the singlet channel with a cross section of at most a few mb plays a marginal role. Then the essential aspects are the octet cross section and lifetime, and more precisely the comparison between the mean free path $l_8 = (\rho_0 \sigma_{(c\bar{c})_{8N}})^{-1}$ and the length traversed in nuclear matter while in octet state. The latter is bounded, on the one hand, by $\gamma \tau_{8 \rightarrow 1}$ (the velocity is almost 1 in the region we consider) and, on the other hand, by twice the nuclear radius, $2R_A$. There are then two extreme regimes:

- $\gamma \tau_{8 \rightarrow 1} \geq 2R_A$. In this regime the suppression is dictated by R_A/l_8 and the x_F dependence comes only from the energy dependence of $\sigma_{(c\bar{c})_{8N}}$ (see Section II). Since the $c\bar{c}N$ center of mass energy is $2x_1 E_p m_p$ and $x_1 \approx x_F$ at large x_F , we expect a slow dependence: $R_A/l_8 \propto (x_F)^{0.2}$. This behavior is too weak to describe the decrease seen at large x_F .

- $2R_A \gg \gamma \tau_{8 \rightarrow 1}$. Here the suppression is set by $\gamma \tau_{8 \rightarrow 1}/l_8$. With $\gamma = x_1 E_p/m_{c\bar{c}}$, the x_F dependence is now $\gamma \tau_{8 \rightarrow 1}/l_8 \propto (x_F)^{1.2}$. This comes close to the observed value. The intermediate regime is an interplay of both scales.

In turn the relation between the two scales may help to fix a maximum octet lifetime by a qualitative look at data. We see in Fig. 1 that the x_F dependence seen in data does not show any clear leveling off except maybe in the region $x_F > 0.6$ in both W to Be and Fe to Be ratios. Taking this x_F as a conservative lower limit for the transition we deduce an upper bound for $\tau_{8 \rightarrow 1}$:

$$\tau_{8 \rightarrow 1} < 2R_{\text{Fe}}/\gamma(x_F = 0.6) = 0.06 \text{ fm.}$$

Notice that using the same reasoning with the fitted value of $\tau_{8 \rightarrow 1}$ one may estimate the value of γ or x_2 at which one sees saturation for a given A . For W we find

$$x_2|_{\text{transition}} = \frac{m_{c\bar{c}} \tau_{8 \rightarrow 1}}{2m_p R_W} \approx 5 \cdot 10^{-3}.$$

We may also go one step further and estimate the regime at work from the actual x_F dependence seen in data. The variation of the number of octet states in a slice of matter may be written as $dN = -N dz/l_8$, i.e. $N(z) = N(z_0) \exp[-(z - z_0)/l_8]$. Combining this indicative exponential behavior with the x_F dependence explained above for the relevant length scale and l_8 , the octet state suppression may be parameterized as

$$S(x_F) = S_0^{(x_F/x_{F_0})^n},$$

where n depends on the regime at work. The value of n may be determined from data by performing the following evaluation

$$n = x_{F_0} \frac{S'(x_{F_0})}{S_0 \ln S_0},$$

where S' is the derivative of S with respect to x_F . At $x_{F_0} = 0.6$ one finds $n \approx 1$ which ensures that the x_F dependence cannot be due to the slowly varying cross section.

The value of $\tau_{8 \rightarrow 1}$ necessary to reproduce data is very short compared to several theoretical estimations [25]. Such a small value has been advocated by Wong [17] referring to an hybrid scenario proposed by Kharzeev and Satz [26] in order to cure these conceptual problems.

The short lifetime may question, however, whether the proposed scenario is realistic at all. The corresponding minimal energy of the gluon emitted for color neutralization is of the order of tens of GeV, which makes no sense. Therefore it may very well be that the octet state is just a parameterization of a much more complicated process. The suppression at large x_F may be attributed to a dispersion of energy in transverse direction. Such an effect is expected if one assumes that the J/ψ 's are not produced directly by gluon fusion but by fragmentation of a color string formed between the nucleons, taking into account the string interactions with surrounding nucleons (the probability to have these final state interactions depending on the length of the path the string travels inside the nucleus). This alternative is currently under a more detailed study.

VII. CONCLUSION

All presently available data including recent results from the E866/NuSea collaboration on J/ψ production in pA collisions can be well described in the standard color neutralization and state expansion scenario with a common set of parameters. This is the result of a Monte-Carlo based model in which this scenario is confronted in detail with data.

It is questionable, however, whether this model is, as far as the color octet state is concerned, more than a well chosen set of fit parameters. The octet lifetime which can be precisely determined by the new data is too short for being understandable in terms of a physical process. Therefore it is probable that the physics observed at large x_F is more complex than assumed up to now.

This parameterization of the production and absorption of charmonium in a hadronic environment could be extended to nucleus-nucleus collisions.

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